REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	23 September 2003	Bi-Annual (Interim) Report, 01 Oct. 2001-30 Sept. 2003

4. TITLE AND SUBTITLE

Sensor Management and Multisensor Fusion Algorithms for Tracking Applications (Bi-Annual Report)

5. FUNDING NUMBERS

Grant N00014-02-1-0136

6. AUTHOR(S)

Lucy Y. Pao

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

Electrical & Computer Engineering Department
University of Colorado
Campus Box 425
Boulder, CO 80309-0425

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

Dr. Rabinder N. Madan, Program Officer
Target Tracking and Sensor Fusion, Office of Naval Research
800 N. Quincy St., Tower One
Arlington, Virginia 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

a. DISTRIBUTION / AVAILABILITY STATEMENT

Unlimited

20030930 123

13. ABSTRACT *(Maximum 200 words)*

The objective of the research under this ONR award is to develop multisensor management and fusion algorithms for tracking applications. Under this award, we have achieved a number of results: (1) We have developed a decorrelated sequence method for distributed fusion that is amenable to general distributed architectures; (2) We have compared a number of recently proposed multisensor multitarget tracking algorithms to better understand which algorithms perform better in certain scenarios; (3) We have developed variance estimation and ranking tools for efficiently comparing multisensor fusion algorithms; and (4) We have developed several schemes for controlling sensor information to achieve covariance goals when tracking interacting targets in cluttered environments. Our results have provided insight as to the relative performance of various multisensor fusion methods, and the results have also provided a basis for assessing the tradeoffs between performance and computational and communication requirements when planning new sensor network architectures or communication link protocols.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Target tracking, data association, sensor fusion, sensor management	4
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

SENSOR MANAGEMENT AND MULTISENSOR FUSION ALGORITHMS FOR TRACKING APPLICATIONS
(ONR Grant N00014-02-1-0136)

Progress Report, September 2003

Lucy Y. Pao
University of Colorado at Boulder

A brief summary of the progress made in research under this grant is given here. The following papers, funded fully or partially under this ONR award, have been submitted or accepted for publication.

[A] W. Khawsuk and L. Y. Pao. "Decorrelated State Estimation for Distributed Tracking of Interacting Targets in Cluttered Environments," *Proc. American Control Conf.*, Anchorage, AK, pp. 899–904, May 2002.

[B] M. K. Kalandros and L. Y. Pao. "Covariance Control for Multisensor Systems," *IEEE Trans. Aerospace Electronic Systems*, 38(4): 1138–1157, Oct. 2002.

[C] L. Trailović and L. Y. Pao. "Variance Estimation and Ranking of Gaussian Mixture Distributions in Target Tracking Applications," *Proc. IEEE Conf. Decision and Control*, Las Vegas, NV, pp. 2195–2201, Dec. 2002.

[D] W. Khawsuk and L. Y. Pao. "Decorrelated State Estimation for Distributed Tracking Using Multiple Sensors in Cluttered Environments," *Proc. American Control Conf.*, Denver, CO, pp. 3208–3214, June 2003.

[E] L. Y. Pao and R. M. Powers. "A Comparison of Several Different Approaches for Target Tracking with Clutter," *Proc. American Control Conf.*, Denver, CO, pp. 3919–3924, June 2003.

[F] L. Trailović and L. Y. Pao. "Position Error Modeling Using Gaussian Mixture Distributions with Application to Comparison of Tracking Algorithms," *Proc. American Control Conf.*, Denver, CO, pp. 1272–1277, June 2003.

[G] L. Trailović and L. Y. Pao. "Computing Budget Allocation for Efficient Ranking and Selection of Variances with Application to Target Tracking Algorithms," accepted for publication in the *IEEE Trans. Automatic Control*, to appear.

[H] L. Trailović and L. Y. Pao. "Variance Estimation and Ranking of Target Tracking Position Errors Modeled Using Gaussian Mixture Distributions," submitted in July 2002 for publication in *Automatica*.

[I] M. K. Kalandros and L. Y. Pao. "Covariance Control for Sensor Management in Cluttered Tracking Environments," submitted in Aug. 2002 for publication in the *AIAA J. Guidance, Control, and Dynamics*.

[J] M. K. Kalandros and L. Y. Pao. "Covariance Control Strategies for Reducing Bias Effects in Interacting Target Scenarios," submitted in July 2003 for publication in *IEEE Trans. Aerospace Electronic Systems*.

[K] M. K. Kalandros, L. Trailović, L. Y. Pao, and Y. Bar-Shalom. "Tutorial on Multisensor Management and Fusion Algorithms for Target Tracking," submitted in Sept. 2003 for the *Proc. American Control Conf.*, Boston, MA, June 2004.

[L] W. Khawsuk and L. Y. Pao. "Distributed Tracking with Feedback in Cluttered Environments Using Decorrelated State Estimation," submitted in Sept. 2003 for the *Proc. American Control Conf.*, Boston, MA, June 2004.

[M] M. Mallick, L. Y. Pao, and K. C. Chang. "Multiple Hypothesis Tracking Based Distributed Fusion Using Decorrelated Pseudo Measurement Sequences," submitted in Sept. 2003 for the *Proc. American Control Conf.*, Boston, MA, June 2004.

RESEARCH ACTIVITIES

The objective of the research under this ONR award is to develop multisensor management and data fusion algorithms for tracking applications. Given a suite of disparate sensors having varying sensing abilities, we are developing sensor management techniques for determining which sensors should be allocated for which targets at various time intervals in order to achieve the desired precisions in tracking the targets. We are also developing a decorrelated sequence technique to decorrelate decentralized target state estimates so that they can then be combined using a number of centralized sensor fusion approaches. As we are developing these multisensor management and data fusion algorithms, we are investigating various methods of implementing as well as efficiently evaluating the algorithms developed. Finally, as we proceed with our research, we always work to focus our efforts so that our results will be useful for Naval tracking and surveillance systems.

Since the beginning of this project in October 2001, we have achieved results in several different areas:

- Multisensor target tracking is often performed using a single processor to monitor several sensors (centralized fusion), but this method is demanding of both computational power and communication bandwidth. Distributed sensor fusion is a method of addressing these limitations. However, the distributed sensor fusion problem is more complex due to the correlation of separate track estimates. We are working to develop a technique for decorrelating target state estimates at decentralized locations so that they can be more easily combined to form global state estimates for targets in the surveillance region [A,D,L,M]. We are currently evaluating computational and communication requirements and Monte Carlo simulation studies are being run so that we can carefully compare the tradeoffs with centralized sensor fusion as well as other distributed fusion algorithms.

- We have begun a study comparing a number of recently proposed multisensor multitarget tracking algorithms [E]. While various tracking techniques have been proposed over the last decade and have been shown to perform "well" in difficult tracking environments, very few detailed comparisons have been made across these algorithms. Our initial results show some delineation on which algorithms perform better in certain scenarios.

- Because Monte Carlo simulation evaluations of multisensor multitarget tracking algorithms are time consuming and expensive, we are developing efficient techniques for comparing such algorithms. Given a fixed computing budget, we have derived an Optimized Computing Budget Allocation (OCBA) algorithm that efficiently compares various sensor fusion algorithms in terms of root-mean-square (RMS) position tracking error [G]. Previous computing budget allocation methods were developed for large manufacturing optimization problems where the performance metric to be compared across designs is the mean. Because RMS position tracking error is a common performance measure used in evaluating sensor fusion algorithms, we investigated the statistics of the RMS position error performance metric and extended previous computing budget allocation ideas to be applicable for efficiently comparing multisensor fusion algorithms.

  In studying the statistics of the position error, we have also developed a better model of the distribution of position error in target tracking algorithms. While it has usually been assumed that the position error has a Gaussian distribution, we have shown [C,F,H] that this is only justified when tracking is "good." When difficult tracking scenarios are considered (which include loss of track or bias caused by target interaction in multi-target tracking), we have shown that the distribution of the position error is more complex. However, this distribution can be well modeled using a mixture of Gaussians [C,F,H], and we have applied a greedy Expectation Maximization (EM) algorithm for estimating the Gaussian mixture parameters. We have also developed variance estimation and ranking tools for such Gaussian mixture distributions.

We have applied the extended OCBA technique for evaluating the optimal order of sensor processing when measurements are received from different quality sensors. We have validated previous results (obtained via time consuming Monte Carlo simulations) with high confidence levels while reducing the computational effort by an order of magnitude. We have further evaluated more general scenarios and have shown with high confidence that when measurements are available from many sensors of varying qualities, it is best to process the data from the sensors in a reverse quality ordering. That is, in order to achieve the lowest overall RMS tracking error, it is optimal to process the worst sensor first, then the next better sensor, and so on until the best sensor is processed.

We have also applied the augmented OCBA approach for ranking and comparing different types of particle filters [F]. We have shown that the position error distribution in difficult non-linear tracking scenarios can be well modeled by Gaussian mixtures and that when the number of particles used in various types of particle filters is small, the OCBA quickly determines with high confidence levels that one type of particle filter (Auxiliary Sampling Importance Resampling particle filter) is superior to several other particle filters that have recently become popular in the literature.

- Using multiple sensors in surveillance systems allows the strengths of one sensor type to compensate for the weaknesses of another and further provides redundance, therefore increasing system robustness. However, because of limited sensor resources and limited processing capabilities, only a subset of the sensors can be allocated to various targets at each time interval. We are developing several schemes for controlling sensor information. In order to keep the mathematics more tractable, we have initially [B] assumed a centralized processing architecture, where the measurements from all sensors are sent to a global processor where the measurements are fused and used for estimating the states (position, velocity, etc.) of the objects in the surveillance region. We have developed several algorithms that maintain a target's state estimate covariance near a desired level without over-taxing the computational resources of a tracking system. Further insights have been provided to guide the selection of effective covariance goals. We have also modeled and evaluated the effects that (inevitable) sensor request delays can have on performance [B].

  While these initial covariance control algorithms were developed for scenarios when only pure filtering is required for tracking, we have also extended the algorithms to address the presence of clutter measurements and the need for data association in such cases [I]. A method of reducing the effects of data association on covariance control algorithms has been outlined using the previously developed scalar "loss of information" factor to model the impact of data association on the uncertainty of the target state estimates . Monte Carlo simulations show that without this factor, the covariance control system is unable to maintain the desired covariance, resulting in a much larger actual covariance level and ultimately a much higher rate of track loss. Use of the loss of information factor generally restores system performance.

  We have further extended the sensor management approach to reduce bias in estimates that results when targets are closely spaced and interact [J]. By developing an efficient technique for assessing whether targets are interacting and determining the "worst" directions of interaction, sensors are allocated to reduce these interactions and hence mitigate bias in the track estimates for such targets.

  We are continuing to explore an approach for developing sensor manager algorithms for decentralized multisensor systems, where we are deriving two computationally efficient techniques that have low communication bandwidth requirements and allow sufficient nodal autonomy.

Outreach Activities and Honors and Awards

I have recently received the following awards and have participated in the following activities and positions in various professional societies to promote research in estimation and sensor fusion:

- 2001–2002 University of Colorado's Council on Research and Creative Work Faculty Fellowship Award.

- Special service recognition award from the American Automatic Control Council (AACC) in May 2002.
- Vice Chair for Invited Sessions for the 2003 American Control Conference.
- Appointed member of the IEEE Control Systems Society Board of Governors for 2003.
- Program Chair for the 2004 American Control Conference.
- Member of the International Federation on Automatic Control (IFAC) Committee on the Past, Present, and Future of Control Education, 2003– .
- Associate Editor for the International Journal of Control, Automation, and Systems, 2003– .
- Invited presentations:
  - *Efficient and Effective Ways of Processing Sensor Information for Tracking Targets in Cluttered Environments*, University of Connecticut, Nov. 2001.
  - *Sensor Fusion Techniques for Tracking Multiple Targets in Cluttered Environments*, Alphatech, Inc., Feb. 2002.
  - *Multisensor Fusion Algorithms for Target Tracking*, Harvard University, Apr. 2002.
  - *Variance Estimation and Ranking with Applications to Target Tracking Algorithms*, George Mason University, Apr. 2003.
  - *Distributed Multisensor Tracking of Interacting Targets in Cluttered Environments*, Orincon Corporation, Apr. 2003.
- Chaired the following sessions at the 2002 American Control Conference:
  - "Estimation" (chair)
  - "Aerospace and Flexible Structures" (chair)
  - "Time-Varying Estimation" (chair)
- Chaired the following sessions at the 2002 IFAC Conference on Mechatronic Systems:
  - "Control of Flexible Structures I" (chair)
  - "Control of Flexible Structures II" (chair)
  - "Haptic Interfaces" (chair)
- Chaired the following sessions at the 2002 IEEE Conference on Decision and Control:
  - "Stochastic Systems" (chair)
  - "Systems with Nonlinear Dynamics" (chair)
- Chaired the following session at the 2003 American Control Conference:
  - "Concurrent Feedback Control Design and Command Shaping" (co-chair)
- Invited to organize a Tutorial Session on Multisensor Management and Fusion Algorithms for Target Tracking for the 2004 American Control Conference [K].

SUMMARY

Our research results will provide insight as to the relative performance of various multisensor management and fusion methods, and the results will also provide a basis for assessing the tradeoffs between performance and computational and communication requirements when planning new sensor network architectures or communication link protocols. We have disseminated our research findings through our publication and outreach activities and our results have been well received by the community.